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Investigating the Effects of Confining Pressure on Cumulative Damage and the Constitutive Behavior of a Particulate Composite Material

C. T. Liu
Air Force Research Laboratory
10 East Saturn Boulevard
Edwards AFB CA 93524-7680, U.S.A.

M. Yen
Material Technology Center
Southern Illinois University at Carbondale
Carbondale, Illinois, U.S.A.
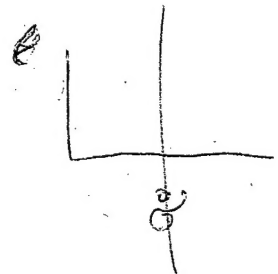
Abstract

In this study, the effect of strain rate on the constitutive behavior and damage state of a particulate composite material under a high confining pressure was investigated. Experimental findings reveal that, for a given strain, the stress and the damage intensity are highly dependent on the strain rate. However, the critical damage intensity is insensitive to the strain rate.

Introduction

Particle reinforced composites are widely used for attaining increased modulus, strength, or toughness depending on the application. Such composites exhibit non-linear constitutive response due to various factors such as damage (debonding, cavity or vacuole formation, cracking), hysteresis during loading-unloading (Mullins effect), viscoelasticity (time-dependence, rate, damage, environment), and large stains (geometric). Such non-linear behavior is observed extensively in filled polymers or rubber products such as toughened plastics, tire, solid propellants and others.

Reliable performance of structures in critical applications depends on assuring that the structures in service satisfy the conditions assumed in design and service life prediction analyses. Reliability assurance requires the accurate structural analysis, which, in turn, requires reliable constitutive models of the material under service load conditions. In past years, a considerable amount of effort was spent in obtaining a fundamental understanding of the effects of strain rate on damage processes and the constitutive behavior in highly filled polymeric materials at ambient pressure [1-4]. In this study, the effects of confining pressure on damage processes and the constitutive behavior of a particulate composite material, containing hard particles embedded in a rubbery matrix, were investigated. A series of constant strain rate tests were conducted at three different strain rates, 0.73 cm/ cm./min., 18.18 cm/cm./min., and 72.73 cm/cm./min., under 6.90 MPa confining pressure. A linear cumulative theory was used to determine the cumulative damage as a function of time under different strain rate loading conditions. The experimental data were analyzed to determine the relationship between the cumulative damage and the constitutive behavior of the material. The results of the analyses are discussed.

The Experiments

In this study, a series tests were conducted on uniaxial dog-bone specimens at three different strain rates (0.73 cm/cm/min, 18.18 cm/cm/min, and 72.73 cm/cm/min) under 6.97 MPa confining pressure. The specimens were made of a highly filled polymeric material, containing hard particles embedded in a rubbery matrix. The dimensions of the specimen are 7.6 cm. long, 0.95 cm. wide, and 1.27 cm. thick. Prior to conducting the tests, the specimen was loaded in the testing machine inside a pressure chamber. When the pressure inside the pressure chamber reached 6.90 MPa, the specimen was straining at a constant strain rate until the specimen fractured. During the test, a high-speed camera was used to monitor the test. In addition, the load and time were also recorded. These raw data were used to determine the stress, the strain, and a damage parameter as functions of time.

Results and Discussion

It is well known that, on the microscopic scale, a highly filled polymeric material can be considered an inhomogeneous material. When these materials are stretched, the different sizes and distribution of filled particles, the different crosslinking density of polymeric chains, and the variation in bond strength between the particles and the binder can produce highly nonhomogeneous local stress and strength fields. Also, this material may contain randomly distributed microvoids, incipient damage sites, and microcracks with statistically distributed sizes and directions. Therefore, the local strength in the material varies in a random fashion, so the failure sites in the material do not necessarily coincide with the maximum stress location. Hence, the failure location as well as the degree of damage induced in the material will also vary in a random fashion. Depending on the magnitude of the local stress and the local strength, damage can be developed in the material, especially near the crack tip region. The damage developed in the material may be in the form of microvoids or microcracks in the binder or dewetting between the binder and the filler particles. When the particle is dewetted, the local stress will be redistributed. With time, additional binder/particle separation and vacuole formation take place. The damage growth in the material may take place as material tearing or as successive nucleation and coalescence of the microcracks. These damage initiation and evolution processes are time-dependent, and are the main factor responsible for the time-sensitivity of the nonlinear constitutive and fracture behavior of the material. It should be pointed that the aforementioned damage initiation and evolution processes are commonly observed in the particulate composite material when the material is subjected to a monotonically increasing load under low confining pressure. However, when the confining pressure is very high, the damage mechanisms may changed, which is a subject of a current study.

Having discussed the damage mechanisms in the particulate composite material, we will now discuss how the damage state affects the constitutive behavior of the material.

Throughout the loading history, the progressive development and interaction of various damage modes change the state of the material, or the mechanical response of the material. In general,

when the particulate composite material is tested under a constant strain rate condition, the initial linear portion of the stress-strain curve is associated with a stretching on undamaged material, with the filler particles bonded to the binder. As the external load is continuously increased, at a certain critical stress level, dewetting occurs. When the density of the dewetted particles reaches a critical value, the rigidity of the material is thereby reduced, and usually this critical dewetting state coincides with the transition from linear response to nonlinear behavior. As the specimen is continuously stretched, the number of dewetted particles is increased, and the formed voids start to grow and coalesce. This damage process is related, primarily, to the nonlinear response of the material, and it can be characterized by bulk volume change during stretching. The bulk volume change during straining is usually known as the strain dilatation, which is partially caused by the nucleation of new voids, and partially caused by the growth of the existing voids. The extent of the volume dilatation depends on the nature of the binder/particle system, the testing temperature, and the strain rate. Therefore, to effectively use the material in structural applications one needs to understand the damage initiation and evolution processes, the effects of damage and crack development on the material's response, and the remaining strength and life of the structures.

A typical plot of stress-strain curves at a constant strain rate of 18.18 cm/cm/min under ambient and 6.90 MPa confining pressures are shown in Fig. 1. From Fig. 1, it is seen that the maximum load increase significantly when the pressure is increased from ambient to 6.90 MPa. However, the magnitude of the confining pressure has no significant effect on Young's modulus. Theoretically, the magnitude of the confining pressure should have no effect on the Young's modulus due to the incompressibility of the material. The slightly variation of the Young's modulus is due to the scatter of the test data, material variability, and the reason that the material is not truly incompressible. It is interesting to point out that under the high confining pressure condition, the critical strain, ε_c, for the transition of the linear response to the non-linear response of the material is increased. Since the material's response is closely related to the damage state in the material, the change of the aforementioned parameters is believed due to the suppression, or the delay, of the development of damage under the higher confining pressure condition. Figure 2 shows the stress-strain curves for different strain rates under 6.90 MPa confining pressure. It is seen that ε_c, ε_m, ε_r, and σ_m increase as the strain rate is increased, and which are typical phenomena observed for rate-sensitivity materials.

In addition to investigating the constitutive behavior of the particulate composite material, a linear cumulative damage theory was used to derive a time-dependent damage parameter,

$$D(t) = \left[\int_0^t \sigma^\beta \, dt \right]^{1/\beta}$$. Plots of D as a function of time for different strain rates are shown in

Fig.3. It is seen that, for a give time, D is highly depended on the strain rate. However, the critical value of D is insensitive to the strain rate. These analytical and experimental findings are consistent with the results of the ultrasonic tests obtained by Liu [5] in his study of cumulative damage in a particulate composite material at different strain rates under ambient pressure condition, using ultrasonic techniques. Typical acoustic data obtained from constant rate tests is shown in Fig. 4. In Fig. 4, the relative changes in the acoustic attenuation coefficient $\Delta\alpha$ are plotted as functions of the applied axial strain and the strain rate. It is noted

that $\Delta\alpha$ is increased as the applied strain and strain rate are increased. Also note that there is a threshold value of strain, ε_{th}, below which no change in acoustic attenuation occurs. The value of ε_{th} decreases with increasing strain rate. Although the threshold value of strain is highly dependent on the strain rate, the rate of change of $\Delta\alpha$ with respect to the applied strain is relatively insensitive to the strain rate as shown in Fig.4. Because the tests were conducted under constant strain rate conditions, the rate of change of $\Delta\alpha$ with respect to time is highly dependent on the strain rate. Since $\Delta\alpha$ correlates with the extent of the internal damage in the material for a given strain level, the increase in $\Delta\alpha$ with increasing strain rate implies that a high strain rate will induce greater damage in the material. It is interesting to point out that the critical value of the acoustic attenuation coefficient, or the critical damage value, is relatively insensitive to the strain rate as shown in Fig. 4. Although the ultrasonic data were obtained from a different particulate composite material and tested at different strain rates and confining pressures, it is believed that the effects of damage on the constitutive behavior of the two materials are similar.

Conclusions

In this study, the effects of confining pressure and strain rate on the constitutive behavior and the damage state in a particulate composite material were investigated. Experimental data reveals that confining pressure has a significant effect on the constitutive behavior of the material. It also reveals that, for a given time, the damage intensity is highly dependent on the strain rate. However, the critical damage intensity is insensitive to the strain rate.

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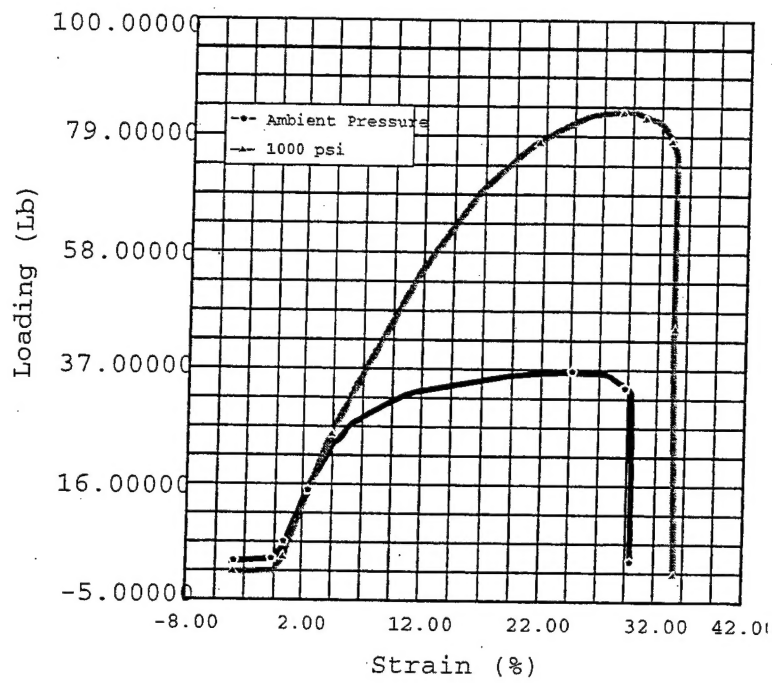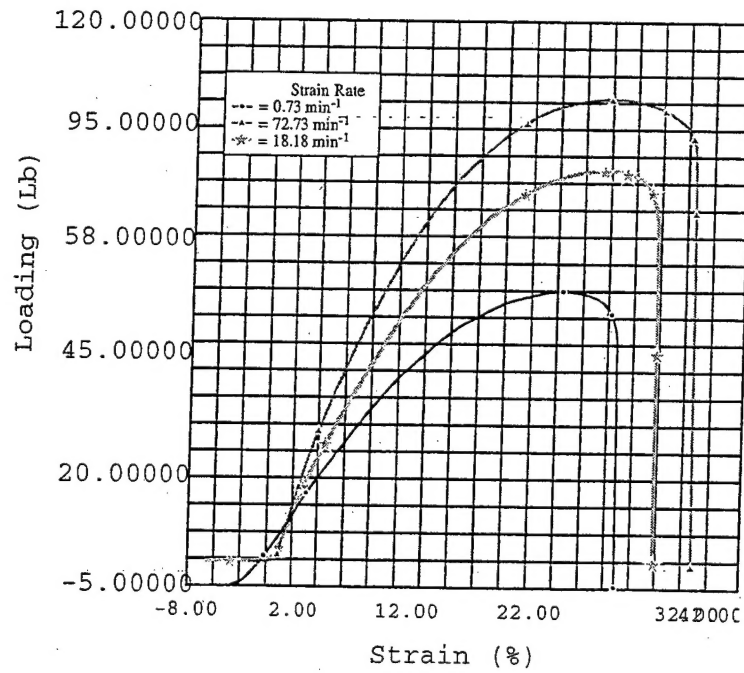
Fig. 1 Applied Load versus Applied Strain

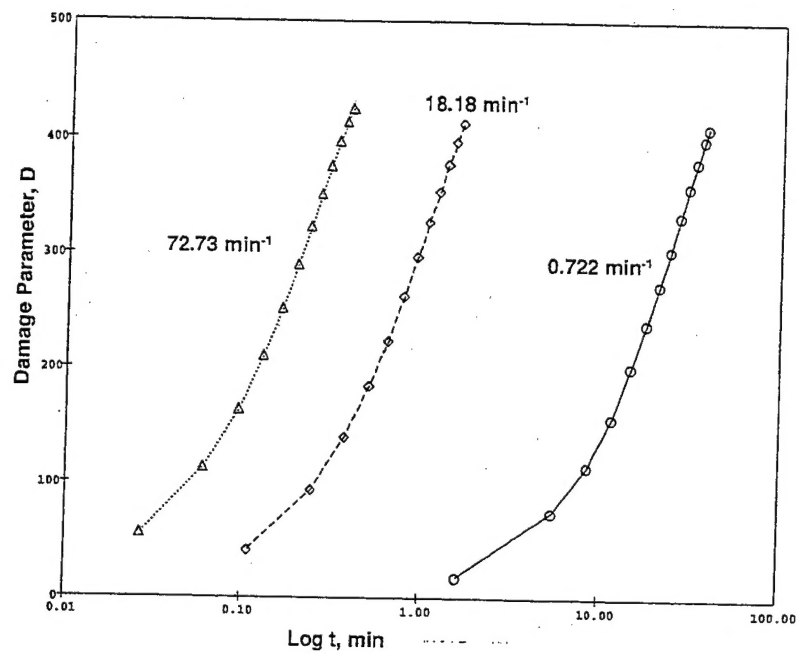Fig. 2 Applied Load versus Applied Strain
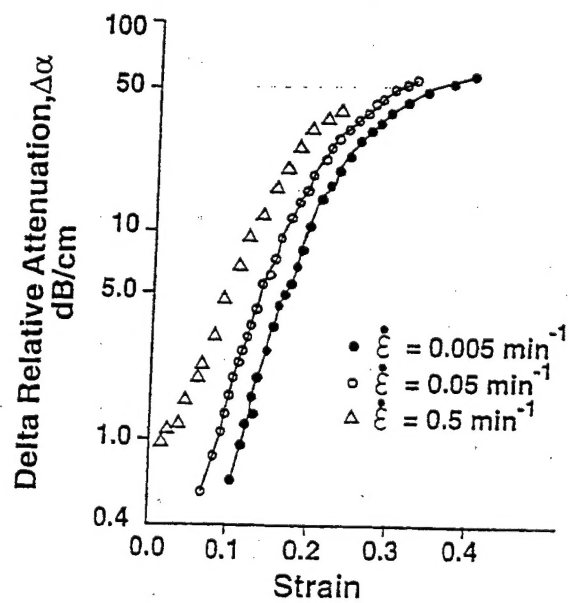
Fig. 3 Damage Parameter versus Time

Fig. 4 Delta Relative Attenuation versus Applied Strain for Different Strain Rates